NASA/TM—2001-211083

ISABE–2001–1017

Recent Developments in U.S. Engine Noise Reduction Research

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Prepared for the
Fifteenth International Symposium on Airbreathing Engines
sponsored by the International Society for Airbreathing Engines
Bangalore, India, September 2–7, 2001

National Aeronautics and
Space Administration

Glenn Research Center

September 2001

Acknowledgments

Many thanks to the hundreds of individuals, from program managers to mechanics, at Allison Rolls-Royce, BBN, Boeing, General Electric, Honeywell, Northrup-Grumman, Pratt & Whitney, and their subcontractors, and at NASA Glenn and Langley Research Centers. Work of this breadth and quality only comes from committed individuals working as a team.

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RECENT DEVELOPMENTS IN U.S. ENGINE NOISE REDUCTION RESEARCH

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ABSTRACT

Aircraft engine noise research in the United States has made considerable progress over the past ten years for both subsonic and supersonic flight applications. The Advanced Subsonic Technology (AST) Noise Reduction Program started in 1994 and will be completed in 2001 without major changes to program plans and funding levels. As a result, significant progress has been made toward the goal of reducing engine source noise by 6 EPNdB (Effective Perceived Noise level in decibels). This paper will summarize some of the significant accomplishments from the subsonic engine noise research performed over the past ten years. The review is by no means comprehensive and only represents a sample of major accomplishments.

INTRODUCTION

Engine noise is one of the dominant sources from today's aircraft, particularly during takeoff. The fan and jet components are the most significant and have been the focus of most of the engine noise research in recent years. Noise reduction is achieved through the combination of low-noise design methods and selecting favorable engine cycle parameters. Significant noise reduction can be achieved by slowing the rotational speed of the fan and lowering the jet exit velocities. Higher bypass ratio engines usually have this feature, such as the GE-90 turbofan engine that was introduced in 1995. In the early 1990's, there was a push to develop Ultra-High Bypass Ratio (UHBR) engines with bypass ratios exceeding thirteen. Much of the early work in NASA's Advanced Subsonic Technology Program was aimed at overcoming the technical challenges associated with the typically very large diameter engines. The major advantages for noise with this engine cycle are the low jet velocities and the lower fan speeds. The jet noise is well below the fan noise and hence research efforts focused on fan noise as the dominant source.

While changing the engine cycle has always been a reliable way to decrease noise, the AST Program also had goals to reduce noise from current turbofan engines. The development and validation of noise prediction tools were regarded as the key to providing low-noise design technologies. The intent was to develop fan and jet noise prediction methods and use them to identify noise reduction technologies that could either be retrofitted to an existing engine or applied to a new centerline engine design. The concepts were validated in model scale wind tunnel tests to confirm acoustic and aerodynamic performance. Many concepts have been tried and are being documented in NASA reports and society papers as the AST Program concludes this year. Some of the concepts are being tested in static engine and flight tests.

The AST Noise Reduction Program has been successful in providing low-noise design technologies and guiding future directions for engine architectures. Work will continue under the new Quiet Aircraft Technology (QAT) Program that started in 2001 and will end in 2005. This program will provide technologies for meeting one of NASA's strategic objective goals to reduce aircraft noise by 10 dB relative to 1997 subsonic aircraft levels. Although this program will not develop technologies to the same readiness level as the AST Program, it will identify propulsion systems for meeting even more stringent noise goals.

The AST Program was led by the NASA Langley Research Center, with support from the Ames and Glenn Research Centers. A team of people from NASA, the FAA, U.S. aerospace companies, and universities participated the research program. A "Technical Working Group" and Steering Committee met every six months to monitor progress. Special focused workshops were used to disseminate technologies to team members. The engine noise reduction research was included in two sub-elements of the program: Engine Noise Reduction and Nacelle Aeroacoustics. The Nacelle Aeroacoustics sub-element was led by the Langley Research Center and concentrated on noise suppression or redirection by modifying the acoustic treatment or the shape of the engine nacelle. The Engine Noise Reduction sub-element was led by the Glenn Research Center and worked on reducing the noise at the source by emphasizing fan and jet noise reduction through design changes. This paper highlights accomplishments from the Engine Noise Reduction sub-element.

AST FAN NOISE REDUCTION PROGRAM

The fan noise reduction element of the AST program sponsored research into cycle-based low-noise concepts for new engines, as well as generic, component-based, concepts aimed at reducing fan noise from existing engines. Through a series of cooperative efforts with the U.S. aerospace companies and universities, a large number of these ideas were developed and tested in NASA aeroacoustic facilities. In what follows, highlights from these efforts will be presented. A more detailed presentation can be found in Reference 1.

Advanced Ducted Propulsor

Incorporating all of the proven pre-AST fan noise reduction technologies, Pratt & Whitney designed and built [2] a scale model fan stage known as the Advanced Ducted Propulsor (ADP), shown in Figure 1, to demonstrate the feasibility of a propulsion system capable of meeting the AST noise reduction goal of 6 EPNdB.

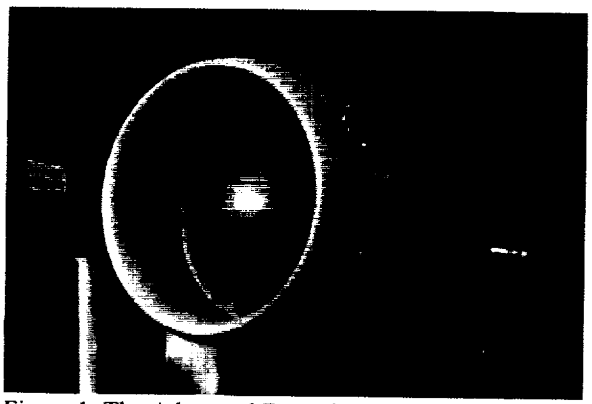

Figure 1. The Advanced Ducted Propulsor 22" scale model fan shown installed in the NASA 9'x15' wind tunnel.

The ADP, which is built around a low tip-speed variable-pitch fan, features large rotor-stator spacing and cut-off vane counts for both the bypass and core stators. The design also takes advantage of advanced liners in the inlet, mid-stage and exhaust sections of the fan duct to further mitigate the noise [3]. Fan casing treatment is used to meet acceptable stall margins and was found to increase the noise by 1 EPNdB. Subsequent tests showed that redesigning the casing treatment to reduce distortions over the fan can reduce the noise to smooth wall levels while maintaining acceptable stall margins [4]. Test results suggest that the ADP will likely fulfill its design goal of meeting the AST engine noise reduction target. However, the ADP represents a departure from the conventional cycle design and it remains to be seen whether it will be embraced by the industry.

Outlet Guide Vane Sweep and Lean

While the potential acoustic benefits of Outlet Guide Vane (OGV) sweep and lean (see Figure 2) had been hinted at in a number of studies throughout the 1970's and 1980's, it was in a joint NASA-Allison test [5] that these benefits were finally quantified and the associated low-noise design rules established.

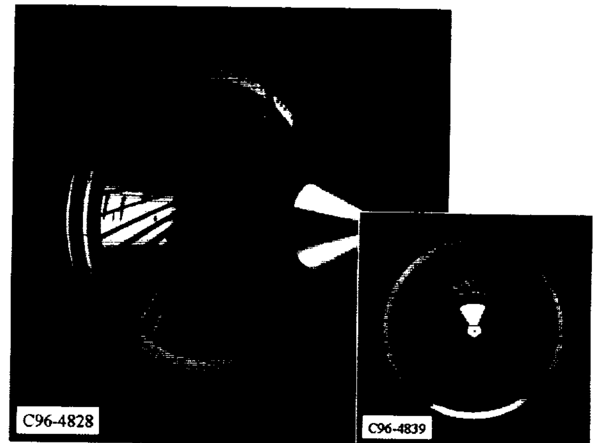

Figure 2. Photograph of the partially assembled fan stage showing the swept and leaned stator (OGV).

The wind tunnel test results showed significant tone and broadband noise reductions with a swept and leaned OGV compared with an aerodynamically equivalent conventional (i.e., radial) OGV. In fact, on an EPNdB basis the results are quite impressive (see Figure 3) showing more than 3 EPNdB noise reductions over the entire range of fan tip speeds for the swept and leaned guide vane compared with the radial guide vane.

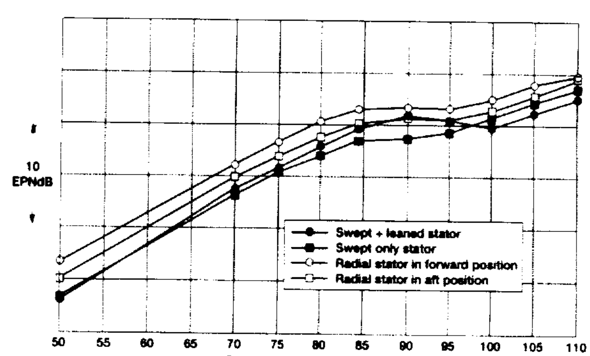

Figure 3. Sideline EPNL for fictitious twin-engine aircraft and flight path. Figure reproduced from Ref. 3.

Active Noise Control

Under the AST noise reduction program, a number of studies were carried out to determine the feasibility of active control of fan noise. As part of these efforts a dedicated Active Noise Control Fan (ANCF) rig was designed and built [6] as the testbed for assessing active noise control. The 4-foot diameter fan has the unique capability for generating specific rotor-stator interaction mode or modes at frequencies similar to those produced by large turbofan engines.

A typical active noise control system has three basic elements: (1) an "actuator" array to produce the canceling acoustic field, (2) an error microphone array to monitor the level of cancellation, and (3) a control algorithm. The actuator array would generally be comprised of an arrangement of resonant-type or electromagnetic drivers installed in the fan inlet or exhaust duct wall(s) and, in one instance, imbedded in the guide vane. Examples of two of the concepts tested as part of the AST program are shown in Figures 4 and 5. Depending on the particular concept and driver arrangement, local control (i.e., inlet *or* exhaust noise cancellation) or global control (i.e., simultaneous inlet *and* exhaust noise cancellation) could be applied.

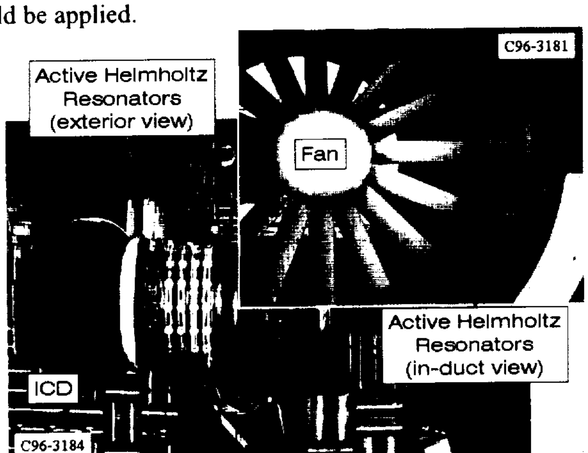

Figure 4. Active Helmholtz resonators drivers in a four-ring arrangement around the duct outer wall upstream of the fan in the inlet duct of the Active Noise Control Fan. View is from inlet duct looking downstream.

A summary of noise reduction results is plotted in Figure 6, which shows the average total PWL reductions versus the number of targeted modes. The results indicate that there are significant noise reduction benefits from the use of active noise control, but that the magnitude of the noise benefits diminishes with increasing number of simultaneously controlled modes. This is partly because the level of control depends on the accuracy with which the microphone array(s) can measure the phase relationships between the simultaneously propagating modes, and the accuracy with which the actuator array(s) can synthesize them. Small errors in measurement and/or synthesis can therefore produce a canceling field that does not exactly match the target field resulting in less noise control (reduction). Since the complexity of the mode phase relationship increases with the number of modes, the control may be less effective when many modes exist compared with the situation when only one or two mode(s) exist. Nevertheless, these results clearly demonstrate the potential of active noise control as a means of reducing fan tone noise, particularly in circumstances where there are only a few dominant modes to be controlled.

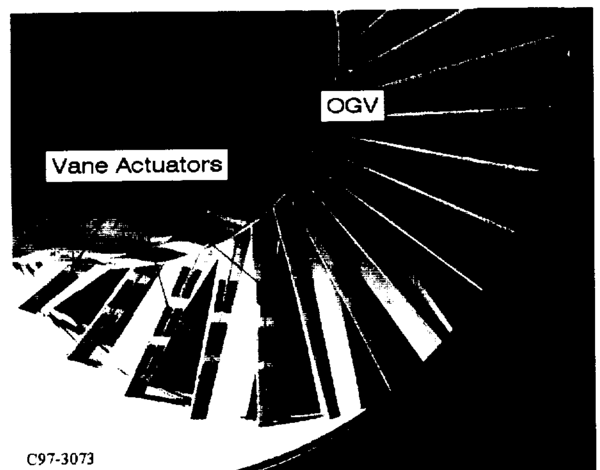

Figure 5. In this technique, the actuators are embedded within the profile of the stator vanes in the ANCF. View is from the exhaust duct looking upstream

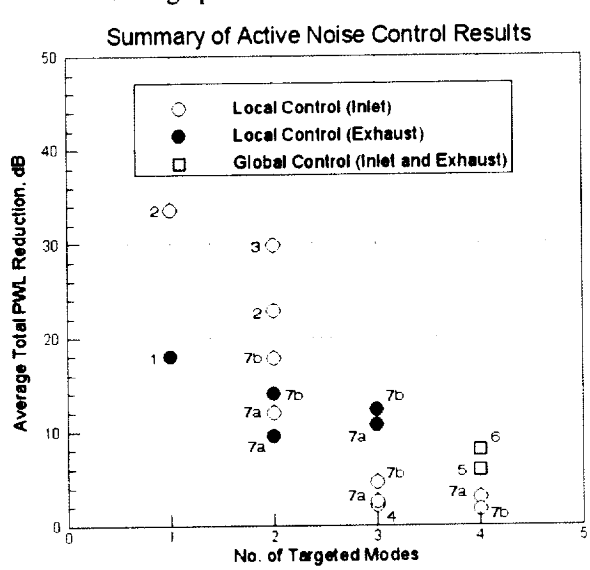

Figure 6. Fan noise level reductions achieved by active control. The labels refer to the test configurations (See Ref. 1 for a description of the data point labels).

Fan Wake Management

A novel approach for reducing fan tone noise involves the use of mass injection at the blade trailing edge to reduce fan wake deficit. In principle, this should render the flow impinging on the downstream stator more uniform leading to lower levels of unsteady loading on the vanes and, hence, less rotor-stator interaction tone noise. Under NASA funding, the Massachusetts Institute of otechnology (MIT) designed a fan to study flow and by implication noise control in a realistic turbomachinery setting [7]. The fan, which is shown in Figure 7, has hollow blades with a labyrinth of internal passages that supply air to trailing edge slots for discharge into the fan wake flow.

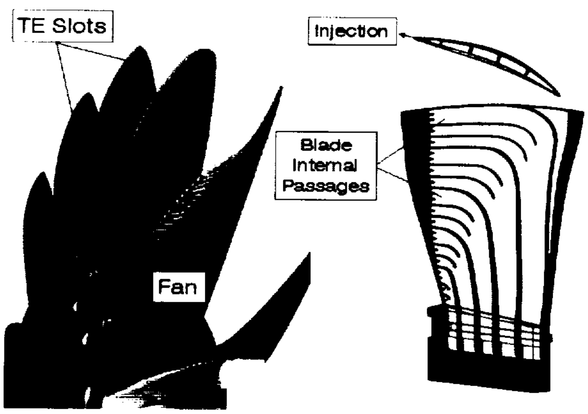

Figure 7. Close-up view of the MIT blown rotor (left) and a detailed view of the blade internal passages. (Reproduced from Ref. 5).

Combinations of several injection rates and profiles were tested using this fan. In each case, the flow downstream of the fan was measured at several axial locations. A typical result is shown in Figure 8. The trailing edge blowing has "filled in" the original wake (solid line) to produce a more uniform mean flow profile (dashed line). On a harmonic basis (see the inset), the trailing edge blowing has reduced the wake harmonic amplitudes by more than a factor of two for the first four harmonics. Although direct noise measurements could not be made during the test due to the non-anechoic nature of the rig, the observed reductions in the amplitudes of the wake harmonics indicate the potential for significant noise level reductions using wake management.

Scarf Inlet

An old concept that was revisited during the AST noise reduction program is the use of a scarf inlet. In theory, the asymmetric shape of a scarf inlet lip, with the lower portion protruding farther forward than the upper portion (see Fig. 9), should shield the observer on the ground from the inlet noise by redirecting the noise upward. A number of studies in the early 1980's had established the potential benefits of "scarfing", but had also indicated a possible problem.

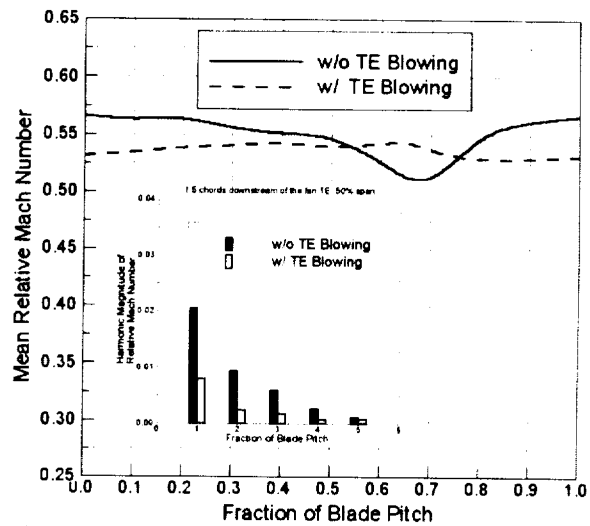

Figure 8. Typical mean relative flow profiles with and without fan trailing edge blowing. The measurements location is downstream of the fan. Inset: Change in harmonic content of the wake due to trailing edge blowing. (Profiles reconstructed from Ref. 5 data).

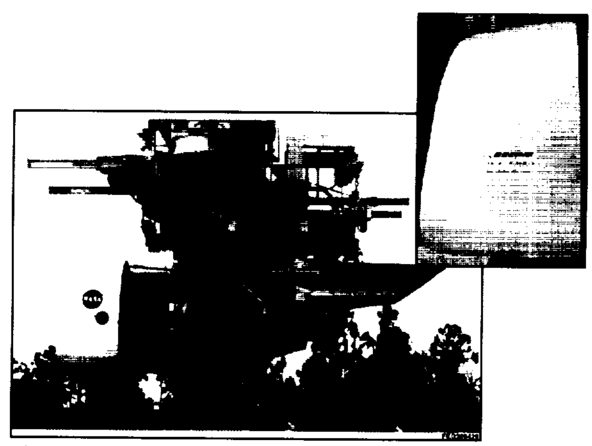

Figure 9. Boeing scarf inlet installed on a Pratt & Whitney PW4098 engine. Photo reproduced from Ref. 6.

With a scarf inlet, the asymmetry can introduce distortions in the flow ingested by the fan which can lead to extraneous noise that could potentially offset the shielding benefits of the scarf inlet. However, recent advances in inlet and treatment design rekindled the interest in the concept. As a result, a full-scale engine test on a Pratt and Whitney PW4098 engine was conducted in the late 1990's which incorporated an advance low-noise scarf inlet designed and built by Boeing [8]. The test was completed in 1999, and even though the inlet aerodynamic and acoustic performance data has not yet been fully analyzed, preliminary results appear quite promising.

AST JET NOISE TEST PROGRAMS

Although the AST jet noise program reached its goal of 3EPNdB noise reduction, the main prize was the detailed flow diagnostic information obtained in model-scale hot jets, information which will lead to jet noise becoming less art and more engineering.

The original focus of the jet noise portion of the AST Program was on internally mixed, long duct nozzles on low and medium bypass ratio engines. To this end a series of contracts were initially awarded to General Electric, Pratt & Whitney, and Allison to explore concepts for improved internal mixers. General Electric undertook a study of mixer concepts with small-scale test hardware first produced in the NASA Energy Efficient Engine program of the early 80's with the objective of providing baseline data with additional flow measurements and testing new nozzles based upon the results of these measurements and CFD. At NASA Glenn, Pratt & Whitney tested enhanced internal mixers for improved acoustic performance and acquired limited flow field turbulence measurements for lower bypass ratio applications. During this test, researchers at NASA Glenn began using mixing enhancement devices called tabs in combination with internal mixers and achieved some success in altering the jet noise [9]. Allison also brought hardware to test at Glenn, primarily focused on the effect of nozzle length downstream of the mixer as an acoustic parameter to be optimized [10].

Although each of these programs produced new insights into jet noise, none of the tests had met the AST goal of 3dB jet noise suppression. With the realization that higher bypass ratio engines would be more important in future fleet mixes, the industry steering committee recommended that a test program be created which would focus on engines with separate flow nozzles. Thus in 1996, planning began on what became the Separate Flow Nozzle Test of 1997 (SFNT97) which will be highlighted here.

The SFNT97 effort brought in ideas from almost all of the engine companies and NASA that were too high risk for industry internal funding. Jet noise technology currently lacks the tools to reliably predict noise from new designs not geometrically similar to an empirical database. Hence, jet noise reduction has historically been done by trial and error and intuition, and in truth not much reduction has been found without an attendant loss of thrust. In this, as in many aspects, SFNT97 was a significant break from the past.

Description of SFNT97

In all, 43 nozzle systems simulating bypass ratios of 5, 8, and 14 with different noise reduction devices were tested acoustically in model scale during the SFNT97 effort. Selected concepts were further explored with other instrumentation, providing takeoff and cruise thrust, perceived acoustic source location, mean pressure and temperatures in the plume, IR images, and schlieren images of density gradients. Details can be found in the primary contractor reports from GE and Pratt & Whitney [11, 12]. An industry workshop held in 1997 first highlighted the many aspects of this test and its proceedings can be found in Ref. 13. Predictive tools relating flow parameters to jet noise are now being developed from this extensive database. Recent tests supported by NASA's Base R&T have added turbulence statistics and nozzle surface static pressure information to this database, providing additional critical data for the creation of analysis tools for jet noise prediction.

Acoustic and Aerodynamic Performance

Of the 43 nozzle systems screened in far-field acoustic measurements, 14 of the most promising were taken to the FluiDyne Aerodynamics Laboratory in Minneapolis, MN to find their takeoff and cruise performance [14]. Figure 10 presents the results of both the acoustic and thrust tests in terms of takeoff EPNL noise reduction and cruise thrust loss for a number of nozzle configurations. The figure shows how the best of the configurations produced over 3EPNdB reduction with less than 0.5% thrust loss. In fact, there were several configurations of enhanced mixers that produced significant noise reduction with minimal thrust loss. Not only did the enhanced mixing nozzles provide an EPNL benefit, they also produced a reduction in total sound power—a reduction in acoustic efficiency in the classic Lighthill U^8 sense.

Progress in Technical Understanding

The theoretical underpinning of designs brought to SFNT97 was that turbulent kinetic energy produces jet noise, particularly in the region 6-10 nozzle diameters downstream of the nozzle. Enhancing the mixing of the core and bypass flows brings about a reduction in the mean velocity, the mean shear, the turbulent kinetic energy, and hence, the generated noise. This has to be balanced against the increase in turbulent kinetic energy produced immediately downstream of the nozzle by the mixing enhancement devices. Thus, the optimum design balances these areas of turbulence. Without the tools to predict the efficiency of conversion from turbulence to sound, the balance must be arrived at by intuition.

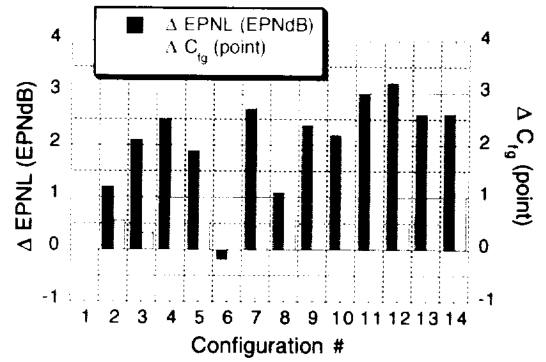

Figure 10 Noise benefits at takeoff and thrust losses at cruise for SFNT97 nozzle systems.

For brevity, analysis of only two nozzle systems are presented here, the baseline (3BB), and alternating 12 chevron core with baseline fan ($3A_{12}B$), both at bypass ratio 5. The $3A_{12}B$ nozzle, shown in Figure 11, typifies the type of nozzle modifications explored in the study.

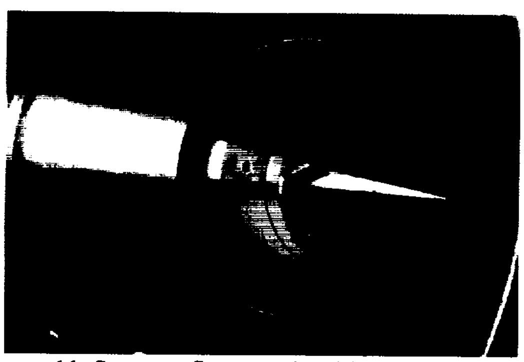

Figure 11. Separate flow nozzle with alternating chevron core nozzle ($3A_{12}B$).

Here, the 12 chevrons were alternately bent inward and outward, resulting in a 6-lobe pattern in the flow field, shown in the time-average velocity field in Figure 12 which was obtained by the plume survey rake using Pt, Tt, and Pstatic probes.

The impact of enhanced mixing on the mean velocity is very evident in this figure. But while reduction of mean velocity would seem to be good for jet noise, it is the turbulence which generates the unsteady pressures that are manifest in far-field sound, and enhancing the mixing usually increases the turbulence. To measure turbulence in a high-speed hot jet, one must turn to advanced measurement technologies, such as Particle Image Velocimetry (PIV). The capabilities of this new measurement technique are illustrated in Figure 13 which shows the instantaneous velocity vectors from a single snapshot in time. Hundreds of these 1080 by 150 point vector fields are acquired in minutes to produce all manner of turbulence statistics once only dreamed of by aeroacoustics researchers.

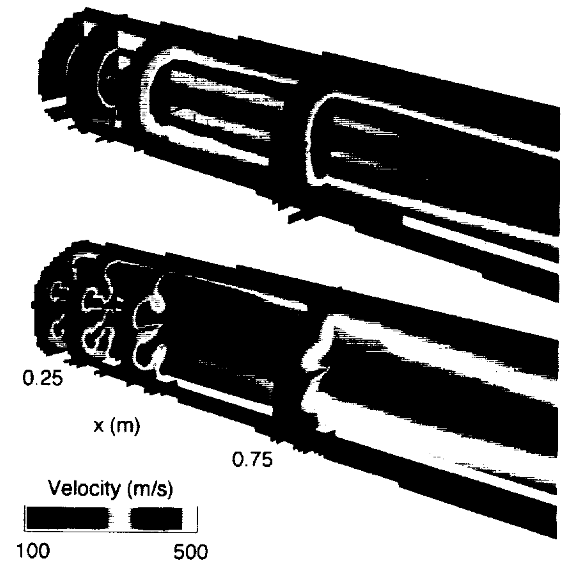

Figure 12. Velocity fields 3BB (above) and $3A_{12}B$ (below) nozzle systems obtained by plume survey rake.

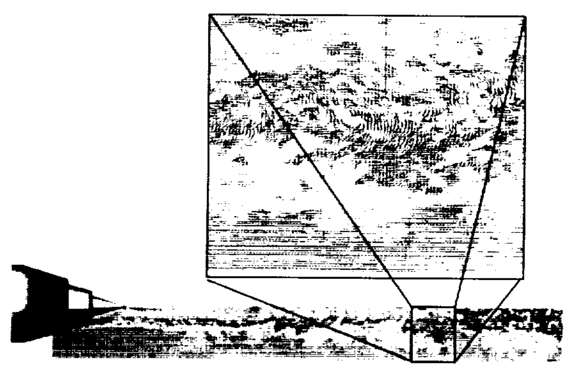

Figure 13. Collage of instantaneous velocity vector fields of 3BB nozzle flow acquired using PIV.

Figure 14 shows how the turbulent kinetic energy has been modified by the chevrons on the core nozzle. The most dramatic change is the reduction in the turbulence at the end of the potential core around 10 fan diameters (2m) downstream. But also note the increase in turbulent kinetic energy 3 – 5 fan diameters (0.5 – 1.0m) downstream of the chevron nozzle. Traditionally, the mixing region 10 diameters downstream has been associated with the low frequency jet noise, while turbulence in regions upstream has been associated with higher frequency noise. In SFNT97 this perception was quantified using phased array techniques, primarily performed by Boeing under subcontract to Pratt & Whitney.

The PIV measurements taken recently at NASA Glenn not only showed how turbulent kinetic energy was reduced in the plume, but also how the energy is distributed in frequency and orientation. Changes in these distributions affect the efficiency of the conversion from turbulence to sound.

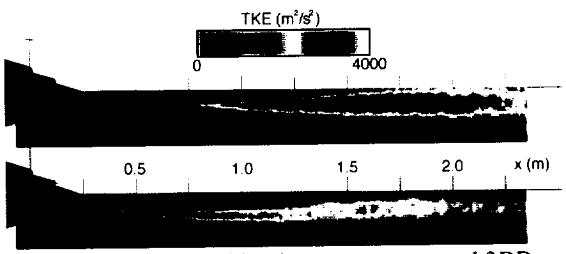

Figure 14. Turbulent kinetic energy measured 3BB (above) and $3A_{12}B$ (below) nozzle systems.

For example, the ratio of axial to radial turbulence, plotted in Figure 15, is very different in the baseline and chevron nozzles. Jet noise theory indicates that this is also a contributor to the noise reduction observed. Current CFD codes cannot predict this distribution, but soon they may if NASA-led efforts in new CFD codes are successful.

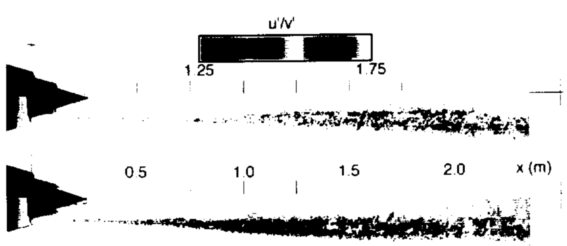

Figure 15. Ratio of turbulence components as measured by PIV for 3BB (above) and $3A_{12}B$ (below) nozzle systems. Fields are masked by turbulent kinetic energy to highlight significant regions.

Another piece of information required to predict the jet noise spectra are the integral lengthscales of the turbulence. These quantities have not been measurable before in a hot, high-speed jet since they require the simultaneous measurement of velocity at multiple points in space, something only feasible with the recent advent of PIV. The integral lengthscales were measured and were found to be unaffected by the chevrons, a surprising result considering other modifications to the turbulence caused by the chevrons.

While the finding of jet noise suppression with insignificant thrust loss was a major success, the real value in the AST jet noise program will be the new insight into jet noise physics obtained during testing. The detailed turbulence data acquired in the SFNT97 and follow-on tests will help on-going jet noise modeling efforts at NASA Glenn [15] and elsewhere, resulting in future reductions in jet noise.

SUMMARY

Fan and jet noise reduction techniques developed as part of the Advanced Subsonic Technology Noise Reduction Program were reviewed. Highlights of developments in low-noise fan stage design, outlet guide vane sweep and lean, active noise control, fan wake management, scarf inlets, and chevron nozzles were presented along with representative results and relevant conclusions (where available). For the most part, enabling technologies for achieving all or part of the 6 EPNdB engine source noise reduction goal have been demonstrated.

For fan noise, further work remains to be done in quantifying the benefits of some of the tested concepts such as the ADP fan, active noise control and scarf inlet, but the outlook appears promising. On the jet side, tests showed actual reduction of jet noise with minimal thrust loss. Beyond measuring performance, extensive diagnostic measurements indicate how to proceed to further reduce and to better predict jet noise.

As for continuing and future work, there is a follow-on test planned for this year at NASA Glenn that is aimed at a careful quantification of the noise benefits from the trailing edge blowing. There has also been some additional testing of the outlet guide vane sweep and lean concept for fan stages with higher tip speeds than the original NASA-Allison fan. These more recent results should help provide a more general assessment of the acoustic benefits of sweep and lean.

NASA will continue to contribute to jet noise reduction technology in the QAT program in three ways. First, by testing high-risk concepts in in-house and cooperative test programs. Second, by acquiring critical diagnostic information not currently available for a wide range of baseline jet flows. Third, in applying the newfound knowledge to NASA's predictive models. For, while jet noise suppression is the most visible goal of NASA's jet noise program, creating the understanding and predictive tools for jet noise reduction is probably the most important.

Given the continuing emphasis on aircraft noise reduction, as indicated by NASA goals to provide technology to reduce noise by 10 dB by the year 2007 and 20 dB by the year 2022, propulsion noise reduction is likely to remain in the forefront of future aircraft noise research.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
September 2001

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Recent Developments in U.S. Engine Noise Reduction Research

5. FUNDING NUMBERS
WU-781-30-15-00

6. AUTHOR(S)
James Bridges, Edmane Envia, and Dennis Huff

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-12927

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM—2001-211083
ISABE–2001-1017

11. SUPPLEMENTARY NOTES
Prepared for the Fifteenth International Symposium on Airbreathing Engines sponsored by the International Society for Airbreathing Engines, Bangalore, India, September 2–7, 2001. Responsible person, James Bridges, organization code 5940, 216–433–2693.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Categories: 01, 07, and 34 Distribution: Nonstandard
Available electronically at http://gltrs.grc.nasa.gov/GLTRS
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Aircraft engine noise research in the United States has made considerable progress over the past 10 years for both subsonic and supersonic flight applications. The Advanced Subsonic Technology (AST) Noise Reduction Program started in 1994 and will be completed in 2001 without major changes to program plans and funding levels. As a result, significant progress has been made toward the goal of reducing engine source noise by 6 EPNdB (Effective Perceived Noise level in decibels). This paper will summarize some of the significant accomplishments from the subsonic engine noise research performed over the past 10 years. The review is by no means comprehensive and only represents a sample of major accomplishments.

14. SUBJECT TERMS
Engine noise; Fan noise; Jet noise; Noise reduction; Turbulence; Subsonic

15. NUMBER OF PAGES
14

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102